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SOILS, SEC 1 • SOIL ORGANIC MATTER DYNAMICS AND NUTRIENT CYCLING • RESEARCH ARTICLE

Land use changes induced soil organic carbon variations in agricultural soils of Fuyang County, China

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Abstract
Purpose The purpose of this study is to understand spatial and temporal variations of soil organic carbon (SOC) under rapid urbanization and support soil and environmental management.
Materials and methods SOC data in 1979 and 2006, of 228 and 1,104 soil samples respectively, were collected from surface agricultural lands in Fuyang County, East of China. Land use data were also gathered at the same time.
Results and discussion The mean SOC was 17.3 (±4.6) g/kg for the 1979 data and 18.5(±5.8) g/kg for 2006. There was a significant difference in SOC between the 2 years according to the *t* test result. Geostatistical analysis indicated that SOC had a moderate spatial correlation controlled by extrinsic anthropogenic activities. The spatial distribution of SOC, derived from ordinary kriging, matched the distribution of industry and urbanization. Using a six-level SOC classification scheme (<3.5, 3.5–5.8, 5.8–11.6, 11.6–17.4, 17.4–23.2, and >23.2 g/kg) created by Zhejiang Province, approximately 15 % of soil had SOC increase from low to high levels from 1979 to 2006.
Conclusions The main cause of SOC variation in the study area was land use change from agriculture to industrial or urbanized uses. The increasing SOC trend near most towns may be attributed to use of organic manure, urban wastes, sewage sludge, and chemical fertilizers on agricultural land.

Keywords Distribution pattern · Geostatistics · Land use · Urbanization

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1 Introduction

The carbon (C) cycle in global terrestrial ecosystems has received increasing attention in recent years due to its association with climate change. On the global scale, about 1,500–2,000 Pg C is stored in the soil organic carbon (SOC), which represents three times higher than the amount of C within plant biomass and twice the amount of C in the atmosphere (Janzen 2004). Moreover, changes in the soil organic carbon pool can influence the concentration of CO_2 in the atmosphere (Smith et al. 2008). Revealing the variation of SOC and understanding its distribution is crucial for developing effective management approaches for reducing atmospheric CO_2 concentrations.

Many factors impact the biogeochemical cycling of SOC and, consequently, impact the distribution of SOC (Dai and Huang 2006; Eynard et al. 2005; Harradine and Jenny 1958). The effects of agricultural land use change on SOC storage have been the focus of numerous studies (Celik 2005; Kong et al. 2009; Solomon et al. 2000), while few investigations cover the influence of transitioning from the agricultural to industrial or urbanized uses on SOC in urban fringe areas. This transition process, however, has resulted in significant human effects on soil quality (Chen 2007) and therefore, should not be neglected in SOC studies.

As the world's largest rapidly developing country, China has experienced a dramatic and unprecedented rate of urbanization since the initiation of economic reform in 1978. There has been a massive transfer from agricultural land use to various other land uses in eastern China due to the rapid urban expansion. At the same time, overwhelming human activity produced a huge amount of urban waste, which is rich in organic matter (Garcia et al. 1992; Pascual et al. 1997). The urban waste, if properly applied to soil, can directly modify the soil's physical, chemical and biological properties (Lax et al. 1994). Application of industrial and municipal sewage can also change soil properties. Li et al. (2003) found that organic matter content of urban sewage sludge could be as high as 696 g/kg, with an average of 384 g/kg in China.

Using conventional statistics and geostatistics, this study investigated the spatial and temporal variability of SOC in Fuyang County during the last three decades. The objectives of this study were to assess spatial and temporal SOC changes, to explore the influence of agricultural land uses, and to investigate the transition from agricultural to industrial or urbanized uses on SOC variation. The information gathered would provide a scientific basis for land management to enhance C storage and conservation in urban–rural transition areas.

2 Materials and methods

2.1 Site description

The study site is located in Fuyang County, northern Zhejiang Province at the east of China (Fig. 1). This county (119°25′00″–120°19′30″ E, 29°44′45″–30°11′58.5″ N) has an area of 1,831 km^2, with a landscape characterized by a mountain and valley topography, with elevation varying from 6 to 1068 m above sea level. The flat plains and low hilly regions, with a relative elevation of less than 150 m, were selected as our study area to minimize the influence of different topography. The study region has a total area of 860 km^2. Currently in the study area, the land use types include five agricultural land use

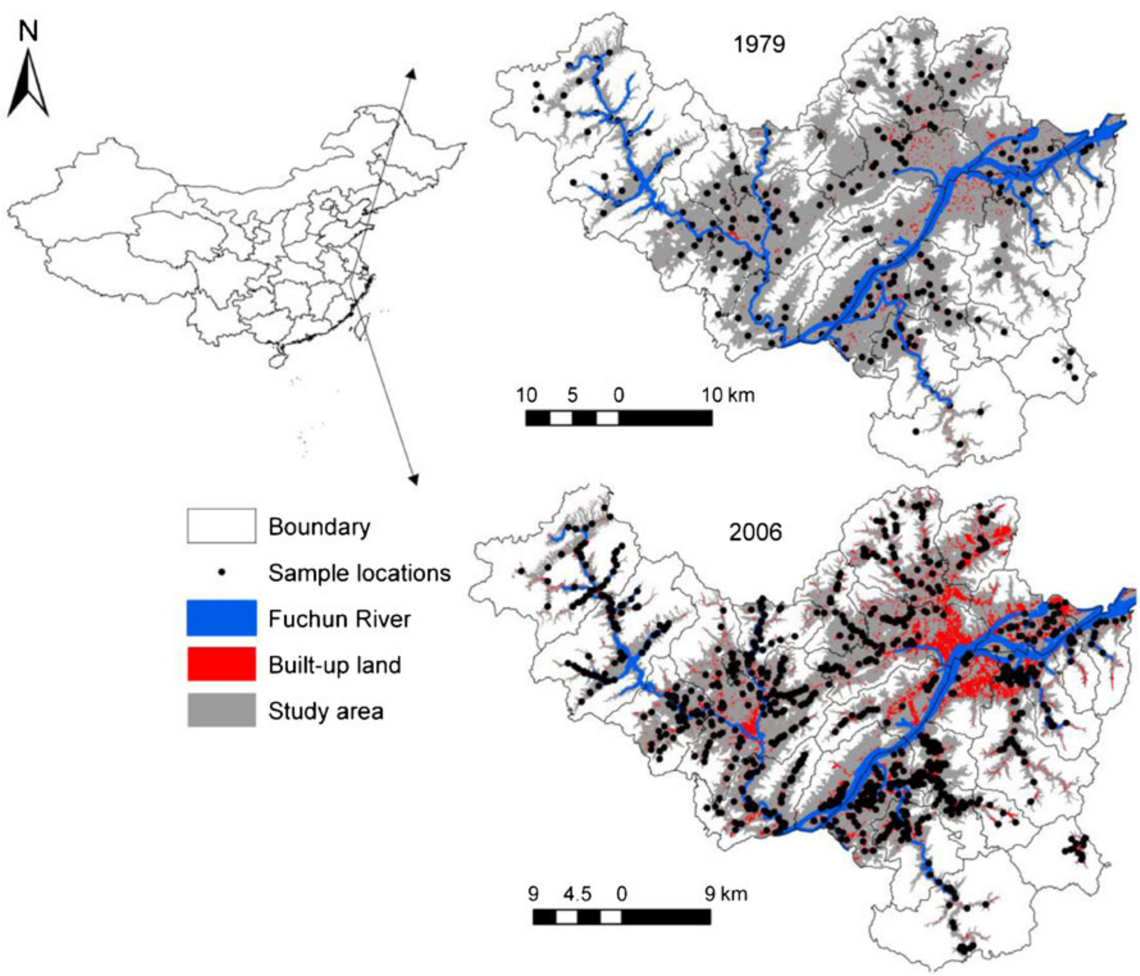

Fig. 1 Location of study area, samples, and spatial distribution of urbanization

Table 1 Summary statistics of soil organic carbon (SOC, gram per kilogram) in study area

Year	*n*	Mean ± SD	Median	Minimum	Maximum	CV	K-S test
1979	228	17.3±4.6	17.7	0.7	29.8	0.27	0.207
2006	1,104	18.5±5.7	18.0	0.6	43.9	0.31	0.085

types (paddy field, dryland, vegetable field, forests, and orchard), built-up land, water body, and vacant land. The subtropical climate (average temperature of 16.1 °C) and high precipitation (1,441.9 mm, annually) make the study area a typical rice paddy production region. The dominant soil types include clay red earth and paddy soil (Zhang et al. 2009).

During the past three decades since the economic reform in 1978, urbanization and industrialization have occurred at an unprecedented pace. The urban population in the county had increased from 38,000 in 1980 to 210,000 in 2006. Urban areas had expanded from 7 km^2 in 1978 to 334.6 km^2 in 2006. The gross domestic product increased from 1.7 billion Chinese yuan in 1978 to 238.4 billion Chinese Yuan in 2006. Fuyang County has become one of the top 100 economically developed counties in China. Paper mills, garment plants, smelting factories, and handicraft workshops have been well-developed and played a very important role in the county's environment (Zhang et al. 2009). The distribution of urban area is presented in Fig. 1.

2.2 Data collection

Soil samples were collected in agricultural land across the study area in 1979 and 2006 to determine the temporal changes in SOC over the 27-year period. The SOC data for 228 samples taken in 1979 and records on sampling locations were obtained from the Bureau of Agriculture of Fuyang County. In 2006, the SOC was measured again for 1,104 soil samples taken in the study area (see Fig. 1). The sampling locations were collocated with the sampling locations from 1979 as exactly as possible. The land use types of sampling locations were also considered. Global positioning systems were used to precisely locate every sampling location. A total of five sampling points were collected, to a depth of up to 20 cm, within a 5-m radius of a specific sampling location; then the samples were mixed and air-dried at room temperature. Stone and plant residue in the soil samples were manually removed, and then the samples were ground to pass a 2-mm sieve. SOC was determined according to the Walkley and Black method (Walkley and Black 1934).

Land use data for 2006, with information on industrial types, was obtained from Bureau of Land and Resources of Fuyang, the land administrator in Fuyang County. The land use map for 1979 was produced by photo-interpretation of 1979 Landsat MSS photographs with a spatial resolution of 30 m (Zhong et al. 2011).

2.3 Data analysis

An important contribution of geostatistics is to assess the uncertainty of unobserved interpolated values (Goovaerts 1997). The semivariogram could be used to quantify the spatial variation of SOC between two points, x and $x+h$, as a function of their distance h:

$$\gamma(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} [Z(x_i) - Z(x_i + h)]^2 \quad (1)$$

Where $Z(x_i)$ and $Z(x_i+h)$ represent the measured value for SOC at location x_i andx_i+h, $y(h)$ is the variogram for a lag distance h, and $N(h)$ is the number of data pairs separated by h. All semivariogram analysis was carried out using GS+® (Version 7). Based on the semivariogram results, ordinary kriging, which is the most common interpolation method, was used to estimate the unobserved SOC values. Ten percent of data points were randomly selected to test the prediction error by the mean prediction error (ME) and root-mean-square standardized prediction error (RMSSE).

$$\mathrm{ME} = \frac{1}{n} \sum_{i=1}^{n} \left[Z(x_i) - z^*(x_i) \right] \quad (2)$$

$$\mathrm{RMSSE} = \sqrt{\frac{1}{n} \sum_{i=1}^{n} \left[\frac{Z(x_i) - z^*(x_i)}{\sigma(x_i)} \right]} \quad (3)$$

Where $Z(x_i)$ and $z^*(x_i)$ represent the measured value and predicted value (respectively) at location of x_i, and $\sigma(x_i)$ is the standard error of prediction at location of x_i.

Table 2 Semivariogram models for soil organic carbon (SOC) in study area

Year	Model	Range (km)	Angle direction	Nugget (C_0)	Sill (C_0+C)	C_0/Sill	ME	RMSSE
1979	Spherical	13.4	48.5	13.6	23.3	0.583	−0.035	0.948
2006	Spherical	4.5	58.5	18.4	35.2	0.523	0.012	0.953

Fig. 2 Distribution maps of soil organic carbon (SOC) content in 1979 (**a**) and 2006 (**b**) in study area, changes in SOC between 1979 and 2006 (**c**)

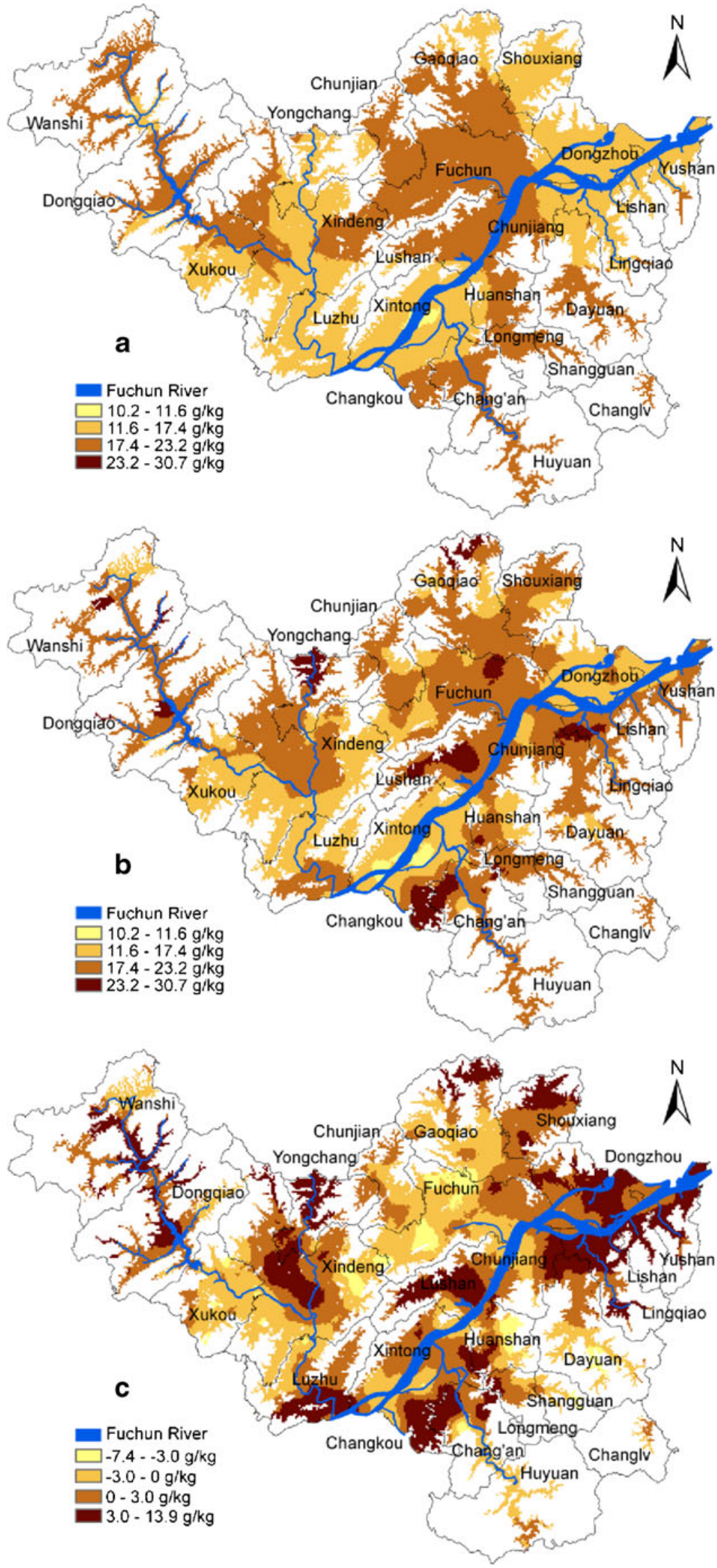

Table 3 Land areas and percentages in different soil organic carbon classes in 1979 and 2006

Time	SOC class (g/kg)	I >23.2	II 17.4–23.2	III 11.6–17.4	IV 5.8–11.6	V 3.5–5.8	VI <3.5
1979	Area (km^2)	–	442.9	416.2	2.9	–	–
	Percentage (%)	–	51.4	48.3	0.3	–	–
2006	Area (km^2)	55.8	511.6	287.4	6.5	–	–
	Percentage (%)	6.5	59.4	33.4	0.7	–	–

Interpolated results were exported as a raster format and consequently resulted in the spatial distribution maps of SOC 1979 and 2006, respectively. Then, the raster calculator was used to get the distribution map of the difference in SOC between 1979 and 2006. Other spatial analyses included overlay analysis, zonal statistics, and buffer analysis. All spatial analyses were done in ArcGIS® (Version 9.2).

Descriptive statistics (mean, median, minimum, maximum, and coefficient of variation) for 1979 and 2006 SOC data were obtained to get a preliminary understanding of the datasets. Normality of the datasets was analyzed using the Kolmogorov–Smirnov (K-S) test. The difference of measurement data was compared with analysis of variance and the *t* test. All statistical analyses were performed using SPSS® (Version 16.0).

3 Results and discussion

3.1 Descriptive statistics

Descriptive statistics for SOC are shown in Table 1. A significant difference in SOC between 1979 and 2006 was detected according to the *t* test results ($P<0.01$). The results indicated that the SOC increased from 1979 to 2006 in the top 20 cm of soil in Fuyang County, on average. According to Zhejiang Province soil survey results (Yu 1994), the SOC was almost unchanged for the soils that were only under natural influence, indicating that anthropogenic factors may have contributed to the increase in SOC in the study area. The K-S test results ($P>0.05$) showed that SOC in Fuyang County was normally distributed in 1979 and 2006, which is a requirement for simple geostatistical analysis. The SOC data were moderately varied, shown by the relatively small coefficients of variation (CV).

3.2 Spatial and temporal distribution pattern of soil organic carbon

The two best-fitted semivariogram models and their parameters are given in Table 2. The theoretical spherical model was the best-fitted for the SOC data. The nuggest-to-sill ratios (C_0/sill) for 1979 and 2006 were more than 50 %, which demonstrated that the SOC had weak spatial correlation with each other (Cambardella et al. 1994). It was in agreement with the decreasing trend in spatial correlation ranging from 13.4 km for 1979 to 4.5 km for 2006.

In order to understand the SOC distribution pattern in two different years, ordinary kriging interpolation was used to generate distribution maps (Fig. 2a, b). Because the mean prediction error (ME) was close to 0 and RMSSE was close to 1 (see Table 2), the interpolated results were considered reasonably reliable. The distribution map for the change of SOC between 1979 and 2006 was obtained by the raster calculation (see Fig. 2c). In 1979, the SOC was low in the northeast and southwest of the county and high in the central and southeast region. By 2006, the SOC in most areas was higher than that in 1979. The lowest SOC content in 2006 was still found in the southwest, but the SOC in the northeast increased significantly. The SOC distribution map for 2006 showed greater variation than in 1979. There were several regions where the SOC was significantly higher than the surrounding area in the 2006 SOC distribution map. According to the distribution map of SOC differences between 1979 and 2006 (see Fig. 2c), the regions where SOC increased the most were situated in the alluvial valley plain of Fuchun River and its tributaries. According to statistical data, most towns located in these regions are well-developed in agriculture and industry. The towns of Dongzhou, Yushan, Lishan, Lingqiao, Lushan, and Shouxiang were traditional agricultural production areas, while the towns of Wanshi, Dongqiao, Yongchang, and Luzhu developed rapidly in the last decade, based on rich resources. The most dramatic

Table 4 Land use changes from 1979 to 2006 in study area (square kilometer)

Year	Built-up	Paddy field	Vegetable field	Dryland	Orchard	Forests	Water body	Vacant land
1979	20.4	461.5	–	–	27.5	339.7	11.0	–
2006	129.2	205.0	10.5	35.5	66.7	352.6	29.9	31.9

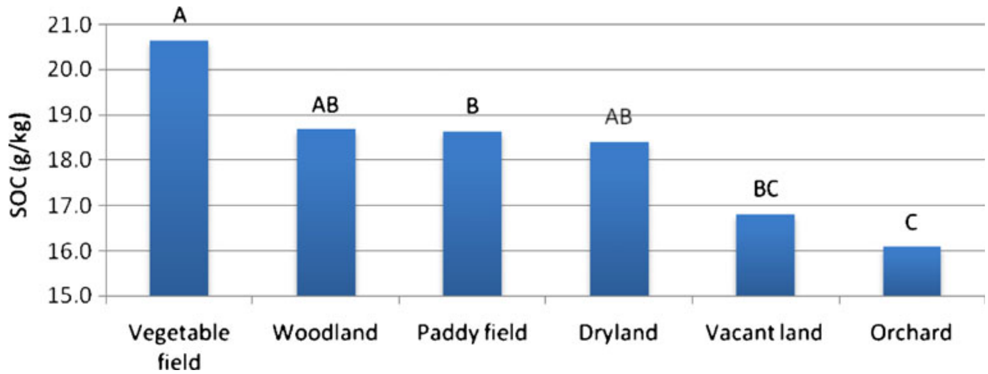

Fig. 3 Mean soil organic carbon content (SOC, gram per kilogram) in different land use types in 2006. The same *letter over the bar* indicates no statistically significant different (LSD)

sprawl of industrialization and urbanization occurred in these regions because of accessibility to traffic and water resources. The spatial distribution pattern of the SOC matched with the distribution of urbanization (see Fig. 1). The SOC increased more near the dense industrial and urbanized areas. Human activities in urbanized areas, including living wastes and domestic and industrial sewage, had impacted the SOC in their neighboring land due to the application of those carbon-rich waste materials.

According to SOC classification standards within the Zhejiang Province (Yu 1994), the SOC in the study area was classified into six levels (Table 3). Generally, the SOC increased in the study area from 1979 to 2006. No soil had the SOC in the highest class in 1979, compared to, 55.8 km^2 of land had the SOC in the highest class in 2006. The land area percentage with the second highest SOC class increased from 51.4 % in 1979 to 59.4 % in 2006. This increase was most probably due to the SOC increase in the soils that were originally the third SOC class, as demonstrated by the decrease of land area categorized with third SOC class from 1979 to 2006. A slight increase in land area with the fourth SOC class from 1979 to 2006 was also observed. All of the previous statistics captured the increasing trend of SOC in Fuyang, but they did not find the decreasing trend in some areas shown in Fig. 2c.

3.3 Land use effects on soil organic carbon

With economic and population growth, built-up land increased greatly from 20.4 km^2 in 1979 to 129.2 km^2 in 2006 (Table 4). Orchards also had a significant increase from 27.5 km^2 in 1979 to 66.7 km^2 in 2006, due to tea plantation area expanding in some towns. Forest areas were stable due to an ecological conservation policy in recent years. Paddy fields dramatically decreased from 461.5 km^2 in 1979 to 205.0 km^2 in 2006, due to transformations to built-up land or other agricultural land use types from paddy fields.

The SOC was significantly different among land use types in 2006 (Fig. 3). Due to high manure input by vegetable farmers, the SOC in vegetable fields was significantly higher than other land use types. The low SOC in Orchards is likely caused by soil erosion because Orchards were mainly planted in the hill slopes (Polyakov and Lal 2004). The SOC was different when paddy fields were changed to another agricultural land use type (Fig. 4). The greatest increase in SOC occurred when paddy fields were converted to vegetable fields in Yongchang, while the greatest decrease was when paddy fields were converted to orchards or vacant land in Fuchun.

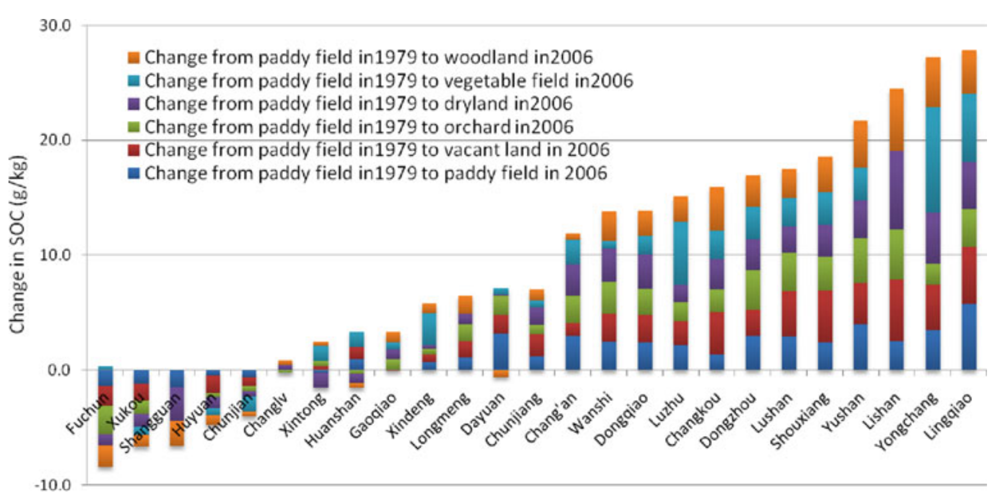

Fig. 4 Changes in soil organic carbon with the changes in land use type in 1979 and 2006

The SOC around most towns increased from 1979 to 2006 (see Fig. 4). These towns are the primary grain-producing regions, where green manure growing area increased over the years since the 1980s and reached 6.1 km^2 in 1990. The area with crop residues left on fields reached 31 % of the total cropping area in 1990 (Agricultural Bureau of Fuyang County 1992). Chemical fertilizer usage has increased to 21,220 t N/year, 4968 t P/year, and 3,018 t K/year. The increase in chemical fertilizer applications has also contributed to the increase in SOC (Liebig et al. 2002). For these reasons, SOC in these towns has significantly increased. West of Fuchun is a primary tea-producing region where the soil surface was severely damaged due to long-term soil erosion. As a result, the SOC decreased significantly from 1979 to 2006 in this region. Xukou is an important fruit- and tea-producing region where a lot of paddy fields, dry land, and forests were transformed into orchards and caused an average decrease in the SOC. Shangguan and Huyuan had few sampling points due to small proportions of cultivated land. Thus, more investigation is needed about SOC in these two towns.

3.4 Built-up land effect on soil organic carbon

Although some towns have similar agricultural land use management practices, SOC increases showed large fluctuations among towns. From Chang'an to Lingqiao (see Fig. 4.), the local government authorized the establishment of an industrial park in nearly every town to accelerate economic development (Zhong et al. 2011). This may have caused a major SOC increase in these towns.

To evaluate the relationship between urbanization and the SOC, SOC variation between 1979 and 2006 around new construction land was analyzed using zonal statistics, depending on grid cell distance to the new construction land. The results demonstrated that the average SOC increased 1.25 g/kg within 200 m of new construction land between 1979 and 2006. The distance from new construction land (x, $100<x<1000$ m) had a significant negative effect on the SOC increase (y) according to the regressive model between them, built as $y=-0.05\ln(x)+1.53$ ($R^2=0.949$, $P<0.05$). Thus, it could be concluded that built-up land has a positive effect on the soil organic carbon increase.

Urbanization and industrial development have a profound impact on the soil environment. Urban people and industries generate tremendous amounts of waste daily. Fuyang County annually discharges 251 million tons of industrial sewage, 0.91 million tons of industrial solid waste, and 17.31 million tons of municipal sewage (Statistical Bureau of Fuyang County 2007). Such a large amount of waste puts tremendous pressure on the soil environment. Currently, comprehensive utilization is the main waste treatment method, which is applied to soil to supply nutrients, organic matter, or as an amendment to restore degraded soils. Applications of municipal solid waste and sewage sludge have proven to be effective in increasing soil organic matter (Pascual et al. 1999; Pedra et al. 2007). Industrial sewage sludge is also a source of SOC with large quantities. Paper manufacturing is one of the most important industries in Fuyang County. There are more than 200 paper mills in the towns of Chunjiang, Yongchang, and Lingqiao. The paper mills discharge 95.5 % of the total industrial sewage in Fuyang. Most of the sewage water from paper mills aggregates to the Fuchun River and its tributaries. The Fuchun River and its tributaries are the main water source for irrigation of farmland along both sides of the river. It has been shown that sewage sludge from paper mills has a positive effect on the SOC increase (Beyer et al. 1997; Foley and Cooperband 2002; Newman et al. 2005).

4 Conclusions

This study investigated the spatial and temporal variability of SOC in Fuyang County, Zhejiang Province, China, during the last three decades using conventional statistics and geostatistics. The results of the present study demonstrate that the average SOC in 2006 was 18.5 g/kg, significantly higher than 17.3 g/kg in 1979. Although on average this difference is small, it was greater in specific areas. The SOC measured in 2006 under peri-urban areas was higher than the under natural conditions. Most of the spatial and temporal variations of the SOC were caused by extrinsic anthropogenic activities. For example, the SOC increased significantly from 1979 to 2006 in the plain along the Fuchun River and its tributaries, where most industrial plants, cultivated land, cities and major towns have emerged since the 1980s. The results also indicate that the changes of agricultural use types and the transitions from agricultural to industrial or urbanized uses were the main factors influencing SOC. Usage of large quantities of organic manure and chemical fertilizers caused overall SOC values of agricultural land uses to increase near most towns. At the same time, urban wastes and industrial sewage sludge applications of soil significantly influenced soil properties and caused the SOC increase.

We conclude that changes in SOC appear to be influenced by both agricultural and industrial activities during rapid urbanization processes. Due to a high demand for soil quality and C storage, it is imperative that judicious land use planning be practiced on a regional basis in the economic expansion process.

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